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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER
TR-3519

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

9

4. TITLE (and Subtitle)

6

DYNAMIC YIELD STRESS AND ELASTIC WAVE VELOCITY MEASUREMENTS FOR HF-1 STEEL.

5. TYPE OF REPORT & PERIOD COVERED
Final Rept.,

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

10

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8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Surface Weapons Center
Dahlgren Laboratory (DG-50)
Dahlgren, VA 22448

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
NAVSEA Task No. SF 32-353-302

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Sea Systems Command
Washington, DC 20362

12. REPORT DATE

11

Sep[redacted]76

12

13. NUMBER OF PAGES
17

16p.

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

14

NSWC/DL-TR-3519

15. SECURITY CLASS. (of this report)
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15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited.

16 SF32-353 17 SF32-353-302

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Shock Waves
Hugoniot Elastic Limit
Wave Propagation
Gas Gun
HF-1 Steel
Elastic Constants

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Shock wave and ultrasonic measurements have been performed on HF-1 steel, heat treated to RC 40 hardness. The dynamic yield stress and elastic wave velocity were determined from precision gas gun experiments. Ultrasonic longitudinal and shear wave velocities were obtained with the pulse-echo technique; Poisson's ratio, Young's modulus, and the one-dimensional static yield stress were calculated. The elastic wave velocity from shock loading agrees favorably with the ultrasonic longitudinal wave velocity.

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S/N 0102-LF-014-6601

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FOREWORD

This report describes the measurement of two important quantities relating to the response of a material to shock loading: the dynamic yield stress and the elastic wave velocity. Results are presented for a fragmentation material, HF-1 steel.

This work was supported in part by NAVSEA Task No. SF 32-353-302, and by NSWC Independent Research funds.

This report has been reviewed and approved by C. L. Dettinger, Acting Head, Munitions Division.

Released by:

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INTRODUCTION

Quantitative information on the response of materials to impulsive loading is important to the design of munitions and armor. The dynamic yield stress and the elastic wave velocity are part of the material parameters used in design computations.

In the past few years a quantitative approach has been developed for characterizing the fracture and fragmentation of materials subjected to shock loading as in armor penetration and cylinder fragmentation.[1,2] This approach involves the experimental determination of the very high strain rate ($\sim 10^5 s^{-1}$) fracture response of a material and computational modeling of the fracture and fragmentation processes. Fracture nucleation and growth data are obtained from gas gun impact and soft recovery experiments on small disk specimens.[3]

The dynamic yield stress, also know as the Hugoniot elastic limit stress (HEL), is the maximum stress amplitude for elastic wave propagation in a material. For higher stress amplitudes the material yields plastically under dynamic loading. As with many of the other mechanical properties, the HEL is affected by microstructural changes resulting from heat treatment.

The material of interest in this report is HF-1 steel, a high carbon and silicon alloy developed by the Bethlehem Steel Company. This steel was heat treated to produce a hardness of RC 40 and a conventional yield stress of 1.04 GPa*. The density is 7.78 Mg/m^3.

* 1 gigapascal (GPa) = 10 kilobars = 145,000 psi.

The specimen thicknesses were 3.19 mm and 6.36 mm, and the diameters were 27.9 mm. Impactor disks for the gas gun experiments were prepared to the same thickness specifications as the specimens, but the diameters were 35.6 mm. The faces of the impactors and specimens were flat and parallel to within 5 μm.

GAS GUN TECHNIQUE FOR MEASUREMENT OF DYNAMIC YIELD STRESS AND ELASTIC WAVE VELOCITY

The dynamic yield stress or HEL was determined for two specimen thicknesses from instrumented impact experiments with a gas gun.[4] A schematic of the gun is shown in Figure 1. The projectile with an appropriate impactor disk is loaded into the barrel and the target is mounted on the muzzle. The barrel is evacuated to minimize gas cushion effects between the impactor and specimen faces at impact. The breech pressure vessel is filled with either helium or nitrogen gas to the desired pressure. The gun is fired by actuating the fast-opening valve.

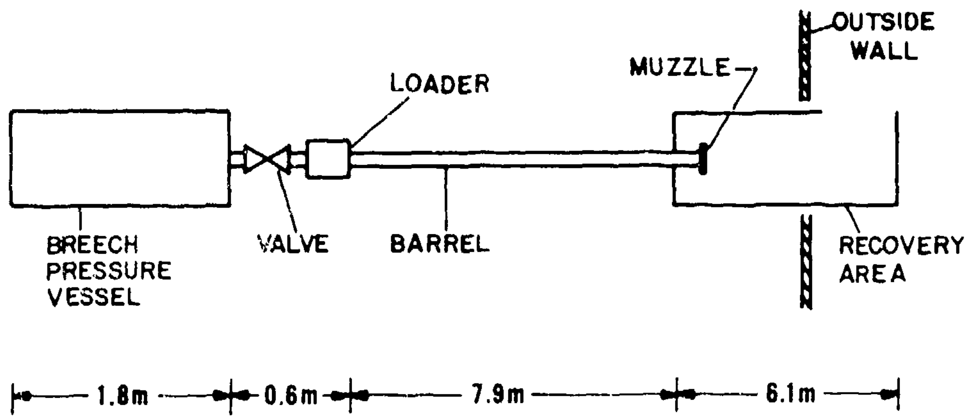


Figure 1. Schematic of Gas Gun

Figure 2 is a schematic of the muzzle region with an instrumented target assembly for HEL and wave velocity measurements. The three pins in the side of the barrel are used with time-interval counters to measure the projectile velocity at impact. Four charged pins surround the specimen and indicate the time at which the specimen surface is impacted. The time sequence of the encoded output pulses gives a measure of the impact planarity or tilt angle. The specimen is backed by a quartz stress gauge (shunted guard-ring type). The current pulse from the gauge can be related to the dynamic stress in the material. Elastic and plastic wave velocities in the specimen can be determined by measuring the time between the impact of the front surface of the specimen and the arrival of stress waves at the back surface.

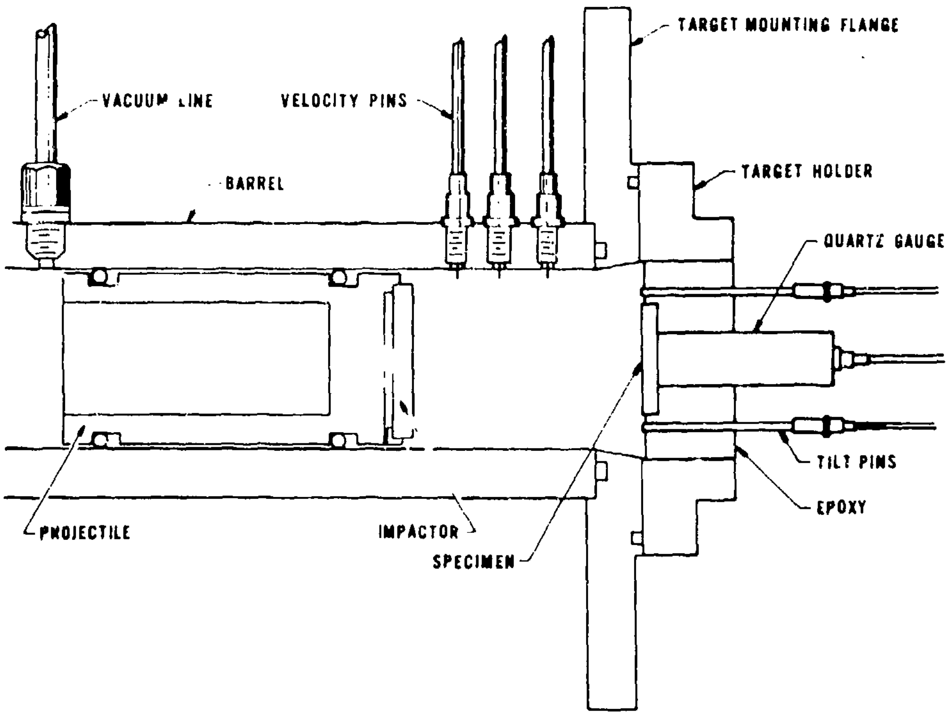


Figure 2. Schematic of Muzzle Region with Impactor and Target Assembly for Stress Wave Measurements

Figure 3 shows the tilt pin data for an HF-1 steel specimen impacted by on HF-1 steel disk at 0.354 km/s. The different voltage steps correspond to the contact of different pins. The tilt angle for this shot was approximately 0.7 mrad. The time reference square pulse is from a Berkeley Nucleonics digital delay generator with 1-ns resolution. This unit generates an initial pulse when triggered by the first tilt pin closure. A second pulse is generated a known time later and displayed on another oscilloscope (operated in the delayed-sweep mode) that records the quartz gauge data. The elastic wave velocity is obtained by using these pulses to measure the time difference between the tilt and quartz gauge signals.

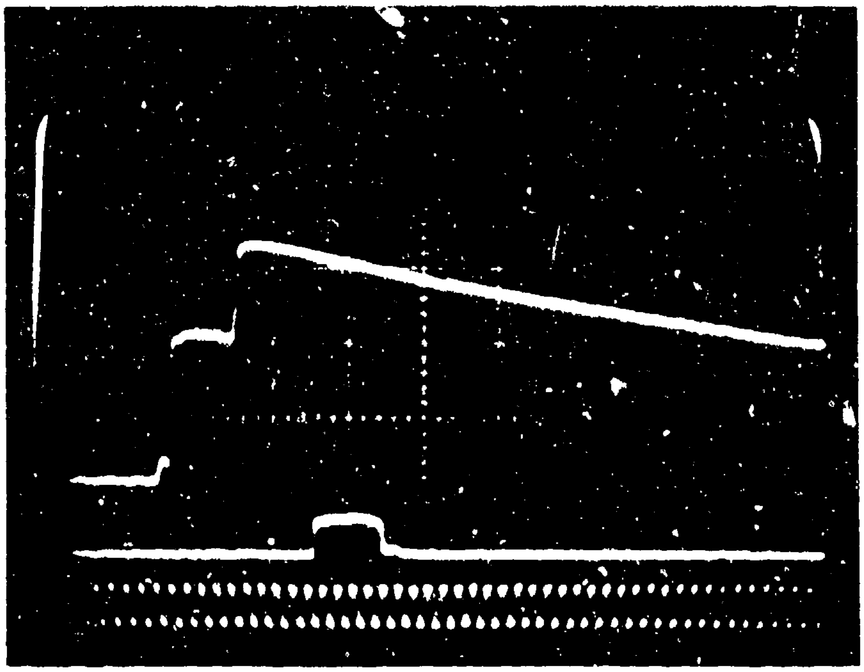


Figure 3. Tilt Pin Data Record (Time increases from left to right. The vertical scale is 4V/div, and the horizontal scale is 50 ns/div. The middle trace is an initial time reference square pulse for wave velocity measurements. The lower trace is a 10-ns-period time calibration signal.)

Figure 4 shows the corresponding quartz gauge current record for the same shot. The leading edge of the upper trace is the elastic wave. The HEL is the stress value at the sharp "knee" in the curve. The slower rise that follows is the plastic wave. A rising transition region occurs between the elastic wave front and the peak of the plastic wave. A similar phenomena has been observed by Jones et al.[5] for SAE 4340 steel and attributed to work hardening and wave dispersion.

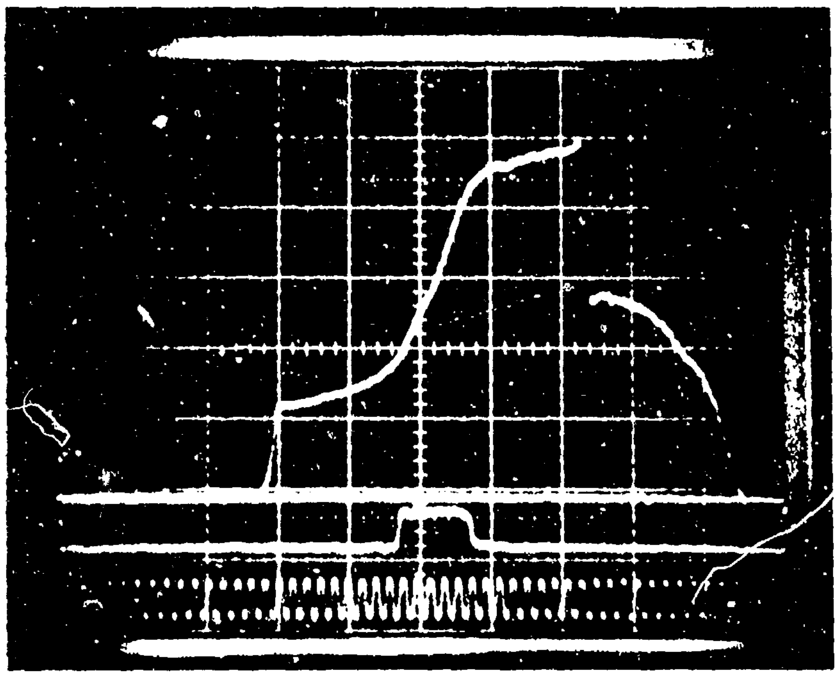


Figure 4. Quartz Stress Gauge Current Record (Time increases from left to right. The middle trace is a delayed time reference square pulse for wave velocity measurements. The vertical scale is 100 mA/div. The lower trace is a 10-ns-period time calibration signal.)

The stress amplitude σ in a linear specimen material is related to the stress σ_q measured by a quartz gauge through

$$\sigma = \left(\frac{Z_q + Z}{2Z_q} \right) \sigma_q \quad ,$$

where $Z = \rho U$ and $Z_q = \rho_q U_q$; ρ, U and ρ_q, U_q are the densities and elastic wave velocities for the specimen material and for the quartz, respectively.[6] Since the dynamic stress-strain relation for this specimen material is assumed to be linear up to the HEL stress value, we have used this equation to calculate the HEL from the experimental parameters.

ULTRASONIC TECHNIQUE FOR MEASUREMENT OF ELASTIC WAVE VELOCITIES

Elastic wave velocities in HF-1 steel were also obtained from ultrasonic measurements using the pulse-echo technique. A fast-rising stress pulse is sent into one face of a disk specimen via a piezoelectric transducer. The same transducer detects the echo pulses internally reflected between the two faces of the specimen. Time differences between successive reflections are measured by monitoring the transducer output with an oscilloscope. The longitudinal wave velocity C_L and the shear wave velocity C_S are then determined using the thickness of the specimen. The elastic constants ν and E, Poisson's ratio and Young's modulus, respectively, are calculated using the following equations for a homogeneous and isotropic material:

$$\nu = \frac{(C_L/C_S)^2 - 2}{2(C_L/C_S)^2 - 2}$$

and

$$E = 2(1 + \nu)\rho C_S^2 \quad .$$

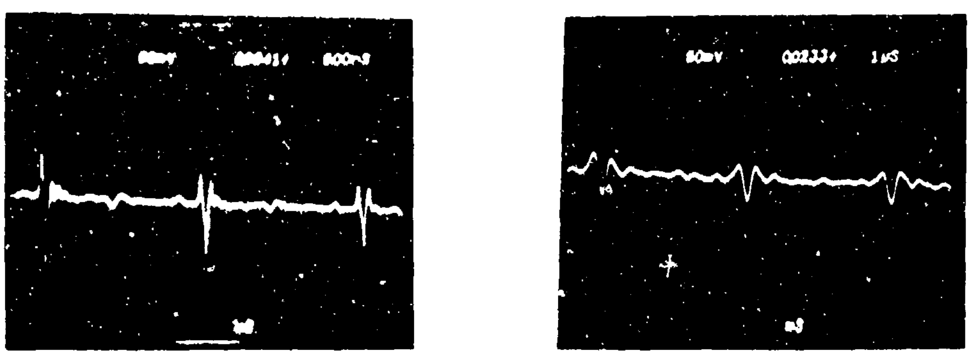
The one-dimensional static yield stress σ_Y can also be calculated:

$$\sigma_Y = \left(\frac{1-\nu}{1-2\nu}\right) Y ,$$

where Y is the conventional yield stress.

The longitudinal wave velocity measurements were performed with 6.5- and 14-MHz Dapco transducers. A 1.6-MHz Panametrics transducer was used for the shear wave velocity determinations. The transducers were used with a Panametrics ultrasonic pulser/receiver. A high viscosity fluid was used to couple the transducers to the specimens. The time between the echos was measured using a Tektronix oscilloscope with a digital delay plug-in unit.

Figure 5 shows ultrasonic pulses for longitudinal and shear wave velocity measurements in HF-1 steel. To measure the time difference between echos, the first positive peak in the pulse is aligned with a selected graticule line; the digital delay unit is then used to move the pulse train across the display in 1-ns increments until the same part of the next pulse is aligned with the fiducial graticule. The elastic wave velocity data were obtained through averaging the time measurements for five or more successive echos for each of two specimens.



(a) (b)

Figure 5. Ultrasonic Pulses for Longitudinal and Shear Wave Velocity Measurements [(a) Longitudinal echo pulses: the vertical scale is 50 mV/div, and the horizontal scale is 0.5 μs/div. (b) Shear echo pulses: the vertical scale is 50 mV/div, and the horizontal scale is 1 μs/div.]

RESULTS AND DISCUSSIO''

The results of two instrumented gas gun shots to obtain the HEL and the elastic wave velocity are shown in Table 1.

Table 1. HEL and Elastic Wave Velocity Measurements

Specimen Thickness (mm)	Impact Velocity (km/s)	Elastic Wave Velocity (km/s)	HEL (GPa)
3.186	0.354	5.94	2.4
6.359	0.339	5.94	2.1

The results of the ultrasonic measurements of the elastic wave velocities and the calculated quantities ν and E are shown in Table 2.

Table 2. Ultrasonic Velocity Measurements and Elastic Constants

Specimen Thickness (mm)	ρ (Mg/m^3)	C_L (km/s)	C_S (km/s)	ν	E (GPa)
6.361	7.775	5.923	3.200	0.2940	0.2060
6.361	7.776	5.923	3.201	0.2938	0.2061

The calculated value of the one-dimensional static yield stress σ_Y is 1.8 GPa. This is almost as large as the average measured dynamic yield stress of 2.3 GPa, indicating only a small amount of strain-rate dependence in HF-1 steel. The measured value of 5.923 km/s for the ultrasonic longitudinal wave velocity is in agreement with the elastic wave velocity of 5.94 km/s obtained under shock conditions with the gas gun.

Jones et al.[5] obtained a value of 2.0 GPa for the HEL of SAE 4340 steel with a thickness of 19.9 mm and a hardness of RC 40. Minshall[7] measured an elastic wave velocity of 5.95 km/s and an HEL of 2.5 GPa for 25.4-mm-thick 4340 steel with a hardness of RC 35. The values in Table 1

for HF-1 steel with a hardness of RC 40 compare favorably with these results for 4340 steel of similar hardness.

SUMMARY

Impact and ultrasonic measurements have been performed on HF-1 steel, heat treated to RC 40 hardness. The Hugoniot elastic limit and the elastic wave velocity were determined from gas gun experiments and compared with values derived from conventional mechanical tests and ultrasonic measurements. The shock results for HF-1 steel are consistent with those for SAE 4340 steel with a similar hardness.

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